Wrist Extensor Torque Production and Discomfort Associated With Low-Frequency and Burst-Modulated Kilohertz-Frequency Currents

Background and Purpose. A randomized controlled trial to compare 2 forms of monophasic pulsed currents with 2 forms of burst-modulated, kilohertz-frequency alternating current (“Russian current” and “Aussie current”) was conducted to establish whether different amounts of wrist extensor torque were produced and whether discomfort varied with stimulus type. Subjects. The 32 subjects were adults who were healthy and were drawn from a population of staff and students at La Trobe University. Methods. Each subject received all 4 currents. Maximal electrically induced torque (MEIT) of the wrist extensors was measured for each stimulus type. Relative discomfort of stimulation also was assessed. Results. Russian current elicited lower mean torque than those elicited by Aussie current and monophasic pulsed currents. The Russian and Aussie currents elicited significantly less discomfort than the 2 monophasic pulsed currents. Discussion and Conclusion. When force production and relative discomfort were jointly used as the criteria, Aussie current was found to be more effective than either of the monophasic pulsed currents or Russian current stimulation. [Ward AR, Oliver WG, Buccella D. Wrist extensor torque production and discomfort associated with low-frequency and burst-modulated kilohertz-frequency currents. Phys Ther. 2006;86:1360–1367.]

Key Words: Alternating current, Maximal electrically induced torque, Pain, Pulsed current, Torque.

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Although electrical stimulation of nerve and muscle has a long history of use by physical therapists, the use of electrical stimulation for muscle strengthening (increasing the force-generating capacity of a muscle) is a more recent development. Interest in this use of electrical stimulation was sparked by talks given by Kots in 1977; in those talks, he described studies showing large strength gains in athletes who received electrical stimulation using 2.5-kHz alternating current (AC) applied in bursts at a frequency of 50 Hz. Kots was not allowed to provide details of his original publications due to “Cold War” restrictions, and they remained unpublicized in the Western world until 2002.

There are only a limited number of published studies in the English-language literature that examine whether “Russian current,” as described by Kots, is effective for muscle strengthening; the evidence is equivocal. At one extreme, a single case study reported by Delitto et al demonstrated substantial strength gains; at the other extreme, the study by St Pierre et al showed no gain.

One study attempted to repeat the Russian work and establish whether 2.5 kHz was an optimal frequency for force production by comparing frequencies in the range of 1 to 15 kHz. Ward and Robertson found that force increased with decreasing frequency, with the greatest force produced at 1 kHz. A later study compared frequencies in the range of 500 Hz to 20 kHz and also showed that 1 kHz was optimal. Although the findings firmly indicate that force production is greatest at 1 kHz, this does not necessarily mean that muscle strengthening will be greatest using this frequency. It seems reasonable to assume, however, that if greater force production results in greater strengthening with voluntary exercise, then greater electrically induced force also will result in greater strengthening. Selkowitz described and discussed the evidence base for this assumption.

Russian current has a burst duty cycle of 50% (ie, a 10-ms burst of AC is followed by a rest period of 10 ms to produce the 50-Hz stimulus). Kots and colleagues originally used continuous AC to establish an optimum AC frequency for force production. They chose a 50% duty cycle and 50-Hz burst frequency on the basis that force production was not reduced compared with continuous (unmodulated) AC stimulation, but the energy delivered to the tissue was halved, so there was a lesser risk of tissue damage. Lower duty cycles were not considered. A recent study, which compared force production at different duty cycles, showed that a duty cycle of 10% (burst duration = 2 milliseconds), rather than 50% (burst duration = 10 milliseconds), was optimal for force production.

Stimulation with kilohertz-frequency AC has the advantage of being relatively comfortable. This was first noted by d’Arsonval, who reported in 1891 that when a constant-voltage AC stimulus is applied transcutaneously, current with a frequency of 1.5 kHz is more painful than current with a frequency of 5 kHz but much more comfortable than 75-Hz and 20-Hz AC. A study by Ward et al, which compared frequencies in the range of 500 Hz to 20 kHz, obtained results consistent with d’Arsonval’s, with the least discomfort occurring at an AC frequency of 4 kHz. The study also showed that a duty cycle of 20% (burst duration = 4 milliseconds) was optimal for minimizing discomfort.

In summary, results to date indicate that, for AC stimulation, 1 kHz is best from the point of view of force production but that 4 kHz is best for minimizing discomfort.
Duty cycle also affects force production and discomfort, with a duty cycle of 10% found to be best for force production, whereas the least discomfort was produced with duty cycles around 20%. A best compromise between force production and discomfort, therefore, seems to be an AC frequency of 1 kHz applied (in 50-Hz bursts) with a 20% duty cycle. As a convenient shorthand, 1-kHz AC applied in bursts with a duration of 4 ms (frequency = 50 Hz) will be referred to as “Aussie” current.

Two questions that have not been addressed in the literature are (1) whether burst-modulated kilohertz-frequency AC stimulation is more comfortable than stimulation with low-frequency pulsed current (PC) and, therefore, more likely to be tolerated by patients and (2) whether kilohertz-frequency AC stimulation results in greater force production. That is, does kilohertz-frequency AC burst stimulation have any advantages (in terms of comfort and force production) over low-frequency PC? A previous study suggests that it might.

The present study was designed to address these questions by comparing “Russian current” (2.5-kHz AC bursts with a 50% duty cycle), “Aussie current” (1-kHz AC with a 20% duty cycle), and 2 conventional monophasic PC stimuli (Fig. 1). The pulse duration of the monophasic PC was chosen to be either 500 microseconds (PC500) or 200 microseconds (PC200). Five hundred microseconds is the phase duration of a 1-kHz AC stimulus and 200 microseconds is that of a 2.5-kHz stimulus. This eliminated pulse duration, and therefore phase charge, as an extraneous variable. The importance of phase charge has been described previously.

Maximal electrically induced torque (MEIT) and relative discomfort were measured for each type of stimulus. There were 2 hypotheses for the investigation. The first hypothesis was that the amount of force produced by Aussie current and monophasic PC would not be significantly different, but that Aussie current would be more comfortable than monophasic PC. The second hypothesis was that Russian current would be more comfortable than monophasic PC, but would elicit less force. These hypotheses were based on the findings of an earlier study. The experimental design was aimed to maximize statistical power by using within-subject measures (ie, each subject experienced all experimental conditions so paired statistical comparisons could be made). This eliminates the effect of between-subject variance that would otherwise be a confounding variable.
Method

Subjects
Thirty-two people volunteered to participate in the study. All volunteers met the inclusion criteria, which required that the subjects have no pathology affecting the left forearm, no pacemaker, and no damage to the skin overlying the wrist extensor muscles. Subjects were recruited from staff and students of the School of Physiotherapy at La Trobe University. The age of the subjects ranged from 19 to 55 years (X = 30.8, SD = 14.5).

Procedure
Subjects participated in a single 15-minute test session. Maximal electrically induced torque was measured, and subjects were asked to inform the investigator if any test conditions felt noticeably more uncomfortable or unpleasant than the others during the ramp-up period. The order of stimulus presentation was quasi-randomized by allocating subjects in an order selected sequentially from a list of the 24 different possible orders of the 4 stimulation conditions.

After the procedure was explained to each subject and informed consent was obtained, the skin of the posterior surface of the left forearm was cleaned using an alcohol swab and conductive rubber electrodes, measuring 44 × 40 mm, were attached using conductive, self-adhesive skin mounts (type 00200-070).* The electrodes were positioned to efficiently stimulate the wrist extensors: on a line from the head of the radius to the distal radioulnar joint with the proximal electrode 1 cm distal to the head of the radius and the distal electrode 5 cm from the proximal electrode along this line. The electrode leads were attached, ensuring that the cathode was the distal electrode (ie, the distal electrode was the negative terminal for the initial half-cycle of the sine wave burst).

The stimulator was a purpose-built device designed to produce constant-voltage stimuli with either a rectangular, monophasic waveform or a burst of sine waves with user selection of the pulse width (PC) or burst frequency and number of sine waves per burst (AC).

The subject’s forearm was secured in a device built expressly for measuring wrist extensor torque, described previously. The wrist axis was aligned with the rotational axis of the apparatus and the forearm and hand were secured with Velcro† straps. A force gauge (model MFG500)‡ (range = 0–500 N, with a resolution of ±0.2 N) connected to the pivoting arm of the apparatus measured wrist extensor torque, calculated as force × distance from the axis of rotation (53 mm). Because the extremely high stiffness of the force gauge prevented rotation about the axis, these measurements were essentially of isometric torque. The device was tested and calibrated before and after the experimental sessions. There was no discernible change in the calibration and the torque/output-voltage relationship was linear to within 0.5%.

Before data collection, each subject was asked to experiment with the stimulus intensity for familiarization. The stimulus used for familiarization was the first listed in the randomized order for that particular subject. The subjects were asked to focus on mentally detaching themselves from the stimulated forearm so they would neither assist nor oppose the electrically induced contraction—to let the stimulator “do the work” without their involvement and to concentrate on relaxation and non-involvement. When subjects reported a satisfactory amount of practice, they were asked to increase the intensity to a level that they regarded as the maximum they could tolerate.

After 2 repeats, partly for familiarization but also to potentiate the extensor muscles, data collection began, following the randomized order of conditions selected for that particular subject. For each condition, the subjects were asked to adjust the stimulus intensity to the “maximum tolerable” level, indicating to the investigator when they had done so, so that 3-second measurements of torque (MEIT), stimulus voltage, and current could be made. This was followed by a 3-second rest interval. The measurements were repeated twice so that 3 measurements were obtained for each test condition. The sequential order of test conditions was then repeated in order to assess the reproducibility of the variation and any fatigue effects.

At the end of the session, subjects were asked whether any of the stimulus types felt more unpleasant or uncomfortable (during the ramp-up or overall) than the others. Our previous (unpublished) observation was that MEITs are sometimes determined by discomfort (ie, the sensation of pain) and sometimes determined by the perception that any greater stimulation would result in physical damage (eg, muscle tearing). Thus, a stimulus type that is reported as more uncomfortable might not produce less MEIT than a comfortable stimulus if the limit of the comfortable stimulus is dictated by a sensation of a muscle tearing or about to tear because the quality of the pain differs. In preliminary experimentation, we also found that the sensations associated with different stimulus types varied in terms of quality and intensity during the ramp-up. It therefore seemed reasonable to make crude comparisons based on simple “more versus less” perceptions of discomfort. The possibility that a recency
effect would influence the subjective assessment of relative discomfort was controlled by the randomized order of presentation of the stimuli.

Data Analysis
Data were analyzed using SPSS version 11 statistical analysis software. The MEIT data were analyzed in 3 stages. First, test-retest reliability was assessed by comparing the 2 sets of MEIT measurements across all subjects and calculating the correlation coefficient (Pearson r). Next, descriptive statistics were obtained for each condition, and tests of normality were made. This was followed by a 2-way (subject × condition) analysis of variance (ANOVA). Finally, post hoc testing, as justified by the ANOVA, was used to test the experimental hypotheses. The number of post hoc tests was kept to a minimum in order to minimize the risk of a type II statistical error. The risk of a type II error is increased when multiple post hoc tests are used and a large Bonferroni correction is needed. Two post hoc tests were made: (1) a 2-factor (subject × condition) ANOVA using only the data for Aussie current and the 2 PC stimuli (PC200 and PC500) to test the hypothesis that there is no significant difference in MEIT elicited by these waveforms and (2) a t test comparing Russian current data with averaged data for Aussie current and the 2 PC stimuli.

Reports of discomfort were analyzed using a nonparametric Friedman 2-way ANOVA by ranks. Post hoc testing, justified by the ANOVA, used a sign test to compare 2 groups: Aussie current + Russian current and PC200 + PC500. The use of a single post hoc test meant that no Bonferroni correction of the acceptable level of significance (α) was needed.

Results

MEIT Measurements
Figure 2 shows the group-averaged MEIT for the 4 conditions examined. Russian current elicited the smallest MEIT, and Aussie current elicited the largest MEIT, with the PC types in between. The standard deviations (indicated by the error bars) were large and, if these were independent group results, one would have to conclude that the differences were insignificant. The repeated-measures, within-subject experimental design, however, allowed between-subject effects to be separated from between-stimulus effects using a 2-factor, without-replication ANOVA. The ANOVA showed a very large and highly significant between-subjects effect ($F_{c} = 55.9; \ F_{c} = 1.57; \ df = 31.3; \ P = 1.4 \times 10^{-17}$). The between–stimulus-type effect ($F = 4.77; \ F_{c} = 2.70; \ df = 3.31; \ P = .04$) also was statistically significant. These findings indicate that the large standard deviations in Figure 2 were due mainly to a large between-subject variation rather than between–stimulus-type variation.

Because 2 measurements of MEIT were obtained for each subject and condition, it was possible to assess the test-retest reliability of the data by comparing the 2 sets of measurements across all subjects. The correlation coefficient (Pearson r) was .94, indicating a high degree of reliability.

Because 4 stimulus types were used there are 6 possible post hoc comparisons that could be made, in which case a Bonferroni-corrected level of significance (α) of $.05/\ 6 = .008$ would have to be used, greatly increasing the risk of a type II statistical error. Because we predicted that differences in MEIT among PC types and Aussie current would be small but that Russian current would elicit significantly less MEIT than the other 3 currents applied, only these 2 hypotheses were tested; therefore, a Bonferroni-corrected α of .025 could be used. To test the hypothesis that there would be no significant difference in the MEITs associated with Aussie current and the 2 PC stimuli, a post hoc, 2-factor, without-replication ANOVA was conducted using only the MEITs for the 2 PC types and Aussie current. The ANOVA showed a very large and highly significant between-subjects effect ($F_{c} = 55.7; \ F_{c} = 1.57; \ df = 31.2; \ P = 1.7 \times 10^{-17}$). The between–stimulus-type effect ($F = 1.52; \ F_{c} = 2.70; \ df = 2.31; \ P = .22$) was statistically insignificant.

A single post hoc t test was then used. Because the ANOVA had demonstrated no significant differences among the Aussie current and the 2 PC stimuli ($P = .22$), data for the Aussie current, PC200, and PC500 were averaged and
compared with Russian current data using a paired t test. Statistical significance was convincingly demonstrated ($t_{51}=5.36$, $P=7.3 \times 10^{-6}$).

Discussion

The second hypothesis tested was that the 2 forms of AC (Russian and Aussie) stimulation would be more comfortable than the PC stimuli. Subjects were asked whether any stimulus type felt more unpleasant or uncomfortable during the ramp-up to maximum tolerable stimulation. Although one would not expect much difference at maximum tolerable intensity, there was clearly a difference in perceived unpleasantness or discomfort during the manual ramp-up. Some subjects nominated 1 stimulus type as being more uncomfortable than the other types, and other subjects nominated 2 stimulus types as being more uncomfortable than the other types. Often the subjects spontaneously described the stimulus identified as more uncomfortable as being more “prickly” or “stabbing” or of more rapid onset than the others. The number of reports of discomfort was tallied and is shown in Figure 3. Preliminary analysis of the results was made using a nonparametric, Friedman 2-way ANOVA by ranks. The ANOVA identified a significant between-stimulus-type variation ($n=32$, $df=3$, $\chi^2=12.0$, $\chi^2_{crit}=11.4$, $P=.01$).

The results shown in Figure 3 suggest that the 2 AC stimuli are more comfortable than the 2 PC stimuli. To test this hypothesis, a sign test was performed comparing 2 groups: Aussie + Russian and PC200 + PC500. Because only one comparison was made, the acceptable level of significance ($\alpha$) was set at .05. The difference found was significant ($n=32$, $z=2.83$, $P=.005$), with the AC stimuli more comfortable than the PC stimuli.

A likely explanation for the findings is that when bursts of kilohertz-frequency AC are used, successive pulses within a burst can summate, with each pulse pushing the nerve fiber membrane closer to threshold until an action potential is produced. If the bursts are long enough, fibers could fire at some multiple of the burst frequency.

The lower MEIT with Russian current (where a burst is 25 cycles of AC) is consistent with fibers firing at multiples of 50 Hz. Firing frequencies above 50 Hz result in what is called “high-frequency fatigue,” where MEIT is reduced either by neurotransmitter depletion or by failure of the action potential to propagate through the muscle fiber. For example, if the firing frequency was 200 Hz when the burst frequency was 50 Hz, neurotransmitter depletion and propagation failure might result in reduced force production. Otsuka et al found that the onset of high-frequency fatigue is sufficiently rapid that it could occur during the manual ramp-up of the stimulus intensity to maximum. The observation that Aussie current and PC produce similar MEITs suggests that the short burst duration of Aussie current does not allow time for multiple firing to occur because there are only 4 cycles per burst. The lower MEIT found with Russian current stimulation suggests that the longer burst duration allows time for multiple firing and consequent high-frequency fatigue, which would be counterproductive for muscle strengthening.

Previous studies have shown that with kilohertz-frequency AC stimulation, the relative discomfort depends on the duty cycle and therefore the burst duration of the stimulus. Ozcan et al found that interferential current (4-kHz AC) is significantly more uncomfortable if the AC is continuous (“true” interferential; 100% duty cycle) rather than delivered in burst

Figure 3.
The number of reports of discomfort (n) for each of the 4 currents examined. PC200=pulsed current at 200 microseconds, PC500=pulsed current at 500 microseconds. The 2 AC stimuli (Russian and Aussie) were significantly less uncomfortable than the 2 pulsed currents.
with a 50% duty cycle (“premodulated interferential”). Ward et al found that a burst duty cycle of about 20% is optimal for minimizing discomfort when the burst frequency is 50 Hz and that single, biphasic AC pulses are more uncomfortable. This raised the question of whether PC is more uncomfortable than stimulation with bursts of AC. A finding of the present study is that the PC stimuli used were indeed perceived as more unpleasant during the ramp-up than the AC bursts \((P=0.005)\).

The reason that bursts of AC are less uncomfortable than PC stimulation is unclear. It may be that summation occurs more effectively with large diameter (sensory and motor) fibers than with smaller diameter (A\(\delta\) and C) fibers; therefore, there is less pain fiber activity induced for a given level of sensory or motor activity with AC bursts. Whatever the explanation, the finding is that burst-modulated AC as used in this study is a more comfortable form of stimulation than PC of the same phase duration.

**Clinical Implications**

The findings of the present study support the notion that kilohertz-frequency AC, as used for Russian current and interferential stimulation, is intrinsically less uncomfortable than PC stimulation \((P=0.005)\). This notion suggests that a greater degree of patient acceptance or adherence would be achieved with AC burst stimulation and may help explain the popularity of Russian and interferential current stimulation in clinical practice.

The present study also showed that PC stimulation, despite being more uncomfortable than Russian current, was more effective in terms of force production and, thus, potentially muscle strengthening. Aussie current \((1-kHz AC with a burst duty cycle of 20\%)\) appears to achieve the “best of both worlds” because torque production is not significantly different from that produced by PC but the discomfort is significantly less. It would be expected, therefore, that Aussie current could achieve similar patient acceptance and adherence to Russian and interferential current stimulation but that force production would not be compromised.

Because one implication of this study is that stimulus types might differ in terms of their effectiveness in muscle strengthening, it would be desirable that a future study test this hypothesis directly using a training protocol (eg, stimulation 3 times per week for 6 weeks) with maximum voluntary contraction as the outcome measure. We note that the present study used subjects who had no injury or muscle impairment, so the findings may not be generalizable. It would clearly be desirable for future studies to compare currents using patient populations and recovery of function or strength as the outcome measures.

**Conclusion**

Russian current, Aussie current, and PC stimuli of the same phase durations were compared in terms of wrist extensor torque production and relative discomfort. We found that the PC stimuli (Russian and Aussie currents) were more comfortable than the 2 PC stimuli. This finding supports the notion that kilohertz-frequency AC stimulation is intrinsically more comfortable than stimulation with low-frequency, short-duration PC and helps justify the continued clinical use of kilohertz-frequency AC.

Previous findings indicate that if the duty cycle is high, force production is reduced.\(^\text{7,17}\) Thus, we anticipated that Aussie current (with a 20% duty cycle) would elicit more force than Russian current (with a 50% duty cycle). Statistical analysis indicated that this was the case. The mean wrist extensor torque with Aussie current \((2.8 \text{ N} \cdot \text{m})\) was 17% higher than with Russian current \((2.4 \text{ N} \cdot \text{m})\). Previous findings\(^\text{7}\) also suggest that single pulses (PC) would elicit less force than Aussie current but that the difference would not be large.

Two conclusions can be drawn from the present study. First, Aussie current produces much the same force as PC, and this is significantly higher than that produced by Russian current. Second, Aussie and Russian currents are a more comfortable form of stimulation than PC. The implication is that Aussie current might be better for muscle strengthening than Russian current or PC because of the greater force production and lesser discomfort. Although there is no significant difference in force production between Aussie current and PC, the discomfort is less, suggesting a greater likelihood of patient acceptance and tolerance when Aussie current is used.

**References**


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